Reflective Silicon Mach Zehnder Modulator With Faraday Rotator Mirror effect for self-coherent transmission

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Abstract: An all-Silicon Reflective Mach Zehnder Modulator (Si-R-MZM) is proposed, providing the Faraday Rotator Mirror effect for achieving simple coherent demodulation. The Si-R-MZM is analytically described and measurements are made to assess the transmission performances.
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1. Introduction

Access Networks systems (Next Generations Passive Optical Networks NG-PON) are forecast to increase the global capacity of broadband access well beyond 40 Gbps downlink and 10 Gbps uplink per feeder, in order to provide a sustained data capacity of 1 Gbps per user. Frequency Domain Multiplexing and Multiple Access (FDM/FDMA) stand as a relevant alternative to Time Domain Multiplexing and Multiple Access (TDMA). Avoiding the need for burst mode operation, these techniques reduce significantly the required bandwidth of the electronic stages at the user location (Optical Network Unit), thus reducing its complexity, cost and power consumption. A Polarization Maintaining fiber-$LiNbO_3$ R-MZM was proposed and demonstrated as a polarization-independent ONU emitter for the uplink transmission, allowing FDMA in combination with coherent demodulation [1]. Furthermore we recently proposed a possible implementation in a full Silicon (Si) integrated version [2], which, in combination with CMOS/ Bi-CMOS electronic stages, would make the architecture suitable for a mass market such as Optical Access. In this paper, we analytically describe the operation of the integrated R-MZM, and discuss its performances considering a Traveling Wave (TW) electrode design. The device is shown to provide the Faraday Rotator Mirror (FRM) effect as long as the R-MZM is biased at π, and the performances of the self-coherent transmission are discussed as a function of the MZM modulation efficiency in the case of co and counter-propagating optical and micro waves. Measurements are made on a TW Si-MZM modulator, showing that the Si-R-MZM has potentially good technical performances, in addition to its economic advantage.

2. Proposed Silicon Reflective Mach Zehnder Modulator with Faraday Rotator Mirror effect

The overall architecture of the uplink transmission, from the User (ONU) to the Central Office (CO) was presented in [1],[2] and is recalled in Figure 1. We propose, here, an improved analytical description of the R-MZM that allows defining the condition for achieving the FRM effect, and the condition for achieving an efficient coherent demodulation. A continuous wave light, represented by the optical field $\xi(t)$, is generated at the CO side by an External Cavity Laser (ECL) with narrow line-width $\Delta\nu$ ($\xi(t) = \sqrt{P_c}.E_o.cos(w_c t + \varphi_c(t))$ where P_c, w_c, and $\varphi_c(t)$ are the laser power, frequency and phase). The optical field is linearly polarized along the TE direction ($E_o = \begin{bmatrix}1\\0\end{bmatrix}$). It is passed through a Polarization Beam Splitter (PBS), and sent to the ONU, through a Single Mode Fiber (SMF) of length L. At the ONU side, the continuous wave light with optical field $\xi_{in}(t)$ ($\xi_{in}(t) = \sqrt{P_c}.\sqrt{L_{Fiber}}.E_{in}(t).cos\big(w_c t + \varphi_c(t - T_{LT})\big)$, where T_{LT} and L_{Fiber} are respectively the time propagation and loss over the fiber length L), enters the fully integrated Si-R-MZM with a random polarization, $E_{in}(t) = \begin{bmatrix}a_{in}\\b_{in}\end{bmatrix}$. A 2D surface grating coupler [2] splits the light into two Transverse Electric (TE) waveguide modes, $TE(CW)in = a_{in}$ and $TE(CCW)in = b_{in}$, propagating, respectively Clock Wise (CW) and Counter Clock Wise (CCW) towards the Si-MZM. A real micro wave signal $u(t)$ is applied to the phase modulation sections (with length L_{el}) of each arm of the Si-MZM, in opposite directions, so that for instance the light polarization a_{in} that turns Clock Wise in the MZM is split into two parts, one which is propagating in the same direction as the micro wave signal $u(t)$(co-propagating micro and optical waves), and one which is propagating in the opposite direction as compared with the micro wave signal $u(t)$ (counter-propagating micro and optical waves). Setting the co-propagating and counter-propagating phase-modulation efficiencies respectively as ε_{co} and $\varepsilon_{counter}$, one can express the optical outputs of the MZM, $TE(CW)out = a_{out}$ and, $TE(CCW)out = b_{out}$ as:

$$a_{out} = {}^{a_{in}}/_{2}\left[exp(-j.\varepsilon_{counter}.u(t)).exp\left(-j\,n_{eff}\frac{\Delta L}{c}w_c\right) + exp(-j.\varepsilon_{co}.u(t))\right] \quad \text{Equation 1}$$

$$b_{out} = {}^{b_{in}}/_{2}\left[exp(-j.\varepsilon_{counter}.u(t)) + exp\left(-jn_{eff}\frac{\Delta L}{c}w_c\right).exp(-j.\varepsilon_{co}.u(t))\right] \quad \text{Equation 2}$$

where ΔL is the path imbalance between the two arms of the MZM, and n_{eff} is the effective index of the optical waveguide. Considering that the path imbalance ΔL between the two arms of the MZM is set such that $n_{eff}\frac{\Delta L}{c}w_c = (2k+1).\pi$, and with the assumption of a small real modulating signal, $u(t)$ such that $\exp(-j.u(t)) \approx 1 - j.u(t)$, Equation 1 and Equation 2 simplify respectively into:

$$a_{out} = -j.u(t).[\varepsilon_{co} - \varepsilon_{counter}].{}^{a_{in}}/_{2} \quad \text{Equation 3}$$

$$b_{out} = +j.u(t).[\varepsilon_{co} - \varepsilon_{counter}].{}^{b_{in}}/_{2} \quad \text{Equation 4}$$

When getting back to the surface grating coupler, the light polarization a_{out} is turned by 90°, while the light polarization b_{out} is kept aligned with the TE direction. The optical field $\xi_{out}(t)$ exiting the Si-R-MZM can be expressed as $\xi_{out}(t) = \sqrt{P_c}.\sqrt{L_{Fiber}}.\sqrt{L_{R-MZM}}.E_{out}(t).cos(w_c t + \varphi_c(t - T_{LT}))$, where L_{R-MZM} are the round trip insertion loss of the Si-R-MZM, and:

$$E_{out} = \begin{bmatrix} b_{out} \\ a_{out} \end{bmatrix} = j.{}^{u(t)}/_{2}.[\varepsilon_{co} - \varepsilon_{counter}].\begin{bmatrix} b_{in} \\ -a_{in} \end{bmatrix} = j.{}^{u(t)}/_{2}.[\varepsilon_{co} - \varepsilon_{counter}].\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}.\begin{bmatrix} a_{in} \\ b_{in} \end{bmatrix} \quad \text{Equation 5}$$

$FRM = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$ is the well-known Jones Matrix of an FRM [4].

The output modulated light $\xi_{out}(t)$ is reflected back, up to the CO. As a result of the well-known benefit of an FRM, after traveling back and forth through the same fiber length, the reflected-modulated light, $\xi_{r,mod}(t)$ ($\xi_{r,mod}(t) = \sqrt{P_c}.L_{Fiber}.\sqrt{L_{R-MZM}}.E_{r,mod}(t).cos(w_c t + \varphi_n(t - 2.T_{LT}))$) will have a polarization orthogonal to the one sent by the ECL. Thus, one can express $E_{r,mod}(t)$ as $E_{r,mod}(t) = j.{}^{u(t)}/_{2}.[\varepsilon_{co} - \varepsilon_{counter}].\begin{bmatrix} 0 \\ -1 \end{bmatrix}$. A coherent photo-detection can thus be made between the polarization-self-aligned modulated light, $\xi_{r,mod}(t)$, and a polarization-rotated-part of the original ECL light $\xi_t(t) = \sqrt{P_c}.[0\ \ 1].cos(w_c t + \varphi_c(t))$ which is used as a local oscillator.

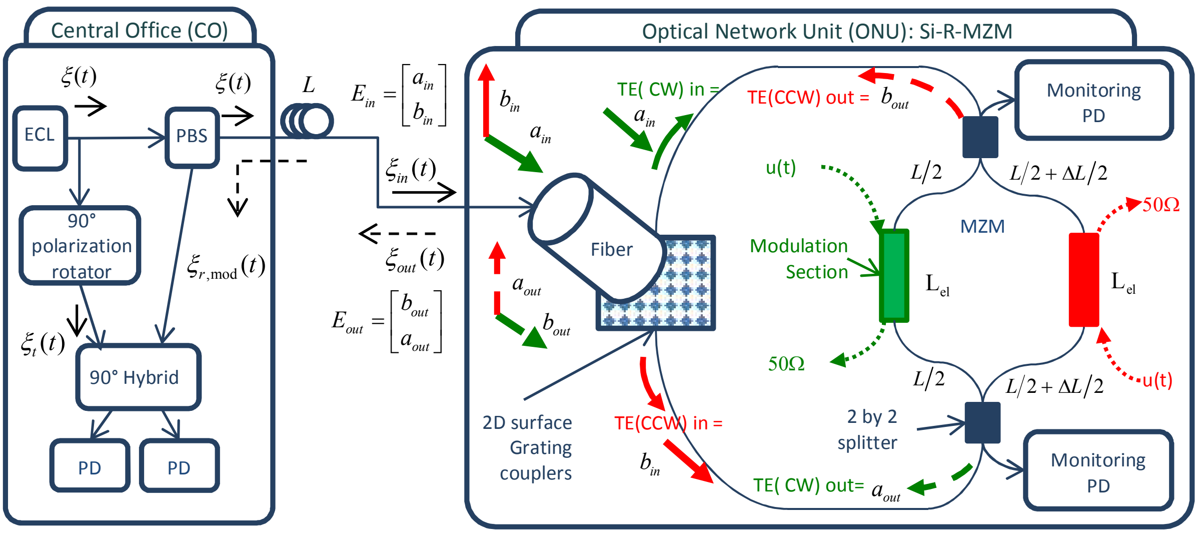

Figure 1- Upstream link schematics

The coherent demodulation produces the optical signal $I(t) = |\langle \xi_t^*(t).\xi_{r,mod}(t)\rangle|$, which can be simplified as:

$$I(t) = \frac{1}{4}.P_c.L_{Fiber}.\sqrt{L_{R-MZM}}.\varepsilon_{co}\left[1 - {}^{\varepsilon_{counter}}/_{\varepsilon_{co}}\right].u(t) \quad \text{Equation 6}$$

As indicated by Equation 6, the proposed device allows a polarization-self-aligned and self-coherent demodulation whose efficiency requires that the counter-propagating phase-modulation efficiency $\varepsilon_{counter}$ is very low as compared with the co-propagating one.

3. Measurements and evaluation of the transmission performances of the Si-R-MZM

In order to evaluate the performances of the Si-R-MZM, we analytically modeled and experimentally measured the residual counter-propagating efficiency in Si-MZMs. We fabricated Si-MZMs, as described in [5], having two different lengths, L_{el} =1mm and 3.5mm, of phase-modulation sections. The latest are made up of a reverse-biased pn junction which is formed in a ridge optical waveguide. Optical phase modulation is achieved by depleting the majority carriers from the reverse biased pn junction, which in turn, varies the effective index of the optical waveguide. A traveling Wave (TW) phase modulation design was implemented: the optical wave travels down the waveguide with a group velocity $v_{go} = c/N_o$, and the microwave driving signal travels along the electrode with the group velocity $v_{gm} = c/N_m$, where c is the speed of light in vacuum and, N_m, and N_o are the group index, respectively of the microwave and optical wave. The co-propagating efficiency bandwidth Δf_{co} due to velocity mismatch is given by [6]: $\Delta f_{co}.L_{el} = 2c/\pi.(N_m - N_o)$. One can derive the counter-propagating efficiency bandwidth $\Delta f_{counter}$, as $\Delta f_{counter}.L_{el} = 2c/\pi.(N_m + N_o)$. Microwave loss along the electrode adds in the limitation of both co and counter propagation bandwidths: they are determined, for a given length, by the skin depth, and one expects a loss in $1/\sqrt{f}$.

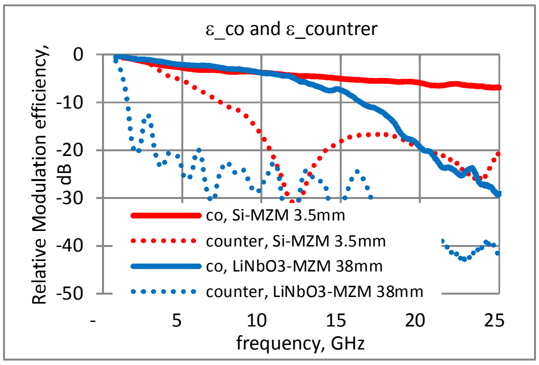

Figure 2a: Measured relative co and counter efficiencies

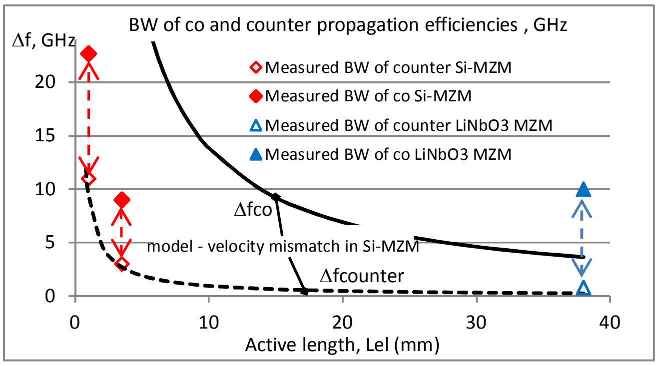

Figure 3b: Measured bandwidth (BW) of co and counter efficiencies versus the length of the phase-modulation section L_{el}

Figure 2a reports the measured co and counter-propagating relative efficiencies of the 3.5mm-long-Si-MZM, as well as that of a commercially available 38mm-long-$LiNbO_3$-MZM. For the Si-MZM (respectively LiNbO3-MZM), the contrast between co and counter modulation efficiencies is > 3dB from 3GHz onwards (respectively from 800MHz onwards for the LiNbO3-MZM). Nevertheless, the usable bandwidth remains comparable, and in the range of ~6GHz (respectively 9GHz for the LiNbO3-MZM), as the roll off of the co-propagating efficiency is lower at high frequencies for the Si-MZM. Figure 2b compares, as a function of L_{el}, the measured co and counter-propagating efficiency bandwidths (BW) with the modeled ones, Δf_{co} and $\Delta f_{counter}$. The measurements made on the Si-MZMs indicate that the counter-propagating efficiency BW is determined by the velocity mismatch, while that of co-propagating is far below the BW determined by velocity mismatch, and is, as experimentally checked, rather limited by the microwave loss along the electrode. This calls for a trade-off between the usable BW and the transmission efficiency, as increasing the electrode lengths will reduce the counter-propagating efficiency BW, for the benefit of a wider usable BW, but will also reduce the co-propagating efficiency BW and the transmission efficiency due to increased electrode loss.

4. Conclusions and Perspectives

First assessment of the R-Si-MZM for use in an FDMA PON scenario shows a 6GHz-usable BW. This compares with a 9GHz usable BW measured with a 38mm-long-LiNbO3 modulator commercially available. As demonstrated in [2], this is largely enough to carry an upstream traffic greater than 20Gbps.

5. Acknowledgements

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